SINGLE MODE FIBER OPTIC SENSOR FOR HIGH CURRENTS

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Summary

We are developing a pulsed current sensor that will be less intrusive than present sensors and that we hope will remain linear to much higher current levels. Polarized laser light is transmitted by a low-birefringence, single mode optical fiber that encircles the current carrier. We observe the Faraday rotation of the polarization plane in the current-induced magnetic field. We have measured a Verdet constant of about 260°/MA for 633 nm light in Lightwave Technologies, Inc., Model F1506C fiber, and we have detected currents of up to 12 MA in pulses 0.5 to 40 μs long. Our major problems have involved signal noise from stray plasma light getting into the fiber and shock-induced birefringence that rotates the polarization slightly. Future plans are to try a Sagnac interferometer to reduce the sensitivity to shock waves.

Introduction

Traditionally, a large, fast current pulse, I, is measured with a Rogowski loop, a wire in which the magnetic flux surrounding the current induces a secondary current proportional to the rate of change in I with time, dI/dt. Although such loops have been used satisfactorily for currents up to a megampere or more, they begin to distort in the large fields present near higher currents and become less accurate. An alternative method for measuring both large currents and high magnetic fields (> 100 T) involves a probe based on the Faraday effect.[1,2] Recent advances in the fabrication of single mode fiber optics have made it possible to build a Faraday effect sensor having almost no intrusion on the system being measured.[3]

Faraday Rotation

The Faraday effect appears as a rotation of the polarization plane of a light wave traversing a medium when there is a magnetic field along the direction of propagation. This rotation arises because the magnetic field induces a circular birefringence, a difference in the refractive indices for the left and right circularly polarized components of the light wave, and the rotation angle is $\Phi = V' \int_0^L B \cdot dx$ where B is the magnetic field, L is the path length in the field and V' is a constant that depends on the medium and the wavelength of the light. For a closed path with current I flowing through the area it bounds, the rotation is $\Phi = VI$, $V = V'\mu_0$, by Ampere's law. For silica glass of the type used in making single mode fibers, the constant V, known as the Verdet constant, is about 260°/MA at a wavelength of 633 nm.[4]

The circular, field-induced birefringence does not combine in a simple way with the linear birefringence caused by internal stresses in the glass and external stresses from clamping, bending, or otherwise applying pressure to the fiber.[4] If either the circular or the linear birefringence is much larger than the other, its effects dominate. Hence we used very low internal birefringence fiber, and we were careful not to bend or clamp the fiber so tightly as to increase its birefringence significantly.

Details of the Sensor

Figure 1 shows a schematic diagram of the Faraday rotation sensor. We insert polarized light from a HeNe laser into the 4 μm fiber core using a 10X microscope objective lens, or we splice the pigtailed output from a single mode, 830 nm diode laser directly to the fiber. Another lens focuses the fiber output into a Wollaston prism which separates the two polarization components and directs them to the two detectors. One detector is a Devar type 539 photodiode and operational amplifier with a bandwidth of 4 MHz used for our early measurements, and the other is an EG&G type FOD-100 photodiode with a Los Alamos transimpedance amplifier having > 100 MHz bandwidth. Presently we run the detectors and laser in a screen room to minimize noise pickup.

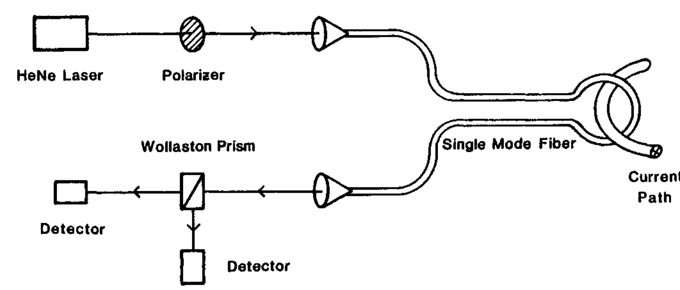

Fig. 1. A schematic diagram of the fiber optic sensor. Polarized light from a laser proceeds down the fiber, around the current carrier, and back to a Wollaston prism which separates the two linear polarization components, directing one component to each detector. When current flows, it rotates the polarization plane and changes the relative detector signals.

We used type F1506C single mode fiber purchased from Lightwave Technologies, Inc. The important features of this fiber are its low internal birefringence and the glass jacket, which has a higher index of refraction than the cladding, to mode-strip out of the fiber any light being transmitted by the cladding. (Similar fibers are manufactured by several other companies.) Since we use short pieces, the fiber attenuation is of relatively little importance to us. For most of our measurements we used a single loop of fiber wound around the current carrier.

We checked the HeNe sensor calibration to ± 5% on a capacitor bank with about 1 MA output current by comparing with a Rogowski loop of known geometry. The calibration accuracy was limited by our ability to determine the rotation angle, but we will repeat this calibration with a sensor having a large number of fiber loops to get an accurate calibration. For the diode laser calibration we scaled the Verdet constant by λ^{-2} to get V = 150°/MA. (Mode dispersion has an effect of about 1%.)

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Our early measurements showed a great deal of detector noise from light that coupled into the fiber core. We eliminated most of this with filters in front of the detectors and black paint sprayed on the part of the fiber inside the vacuum chamber. Some EMI noise remains on the detector signals, particularly for the Devar detector, but by paying careful attention to shielding and fabrication details, EG&G was able to reduce the noise on the newer detector to a satisfactory level.

Results

Figure 2a shows oscillograms of signals from two detectors measuring the orthogonal light components from a fiber encircling a capacitor bank load four times. Each on-off cycle represents a 180° rotation of the polarization plane, or about 0.17 MA change in the load current. The current rose to a peak of 5 MA in 6 μs and then began to drop, at which time the polarization rotation reversed. After another 12 μs the current reversed again. The 2-μs-wide peak at 14 μs in the lower trace is a fiducial timing marker.

(a)

(b)

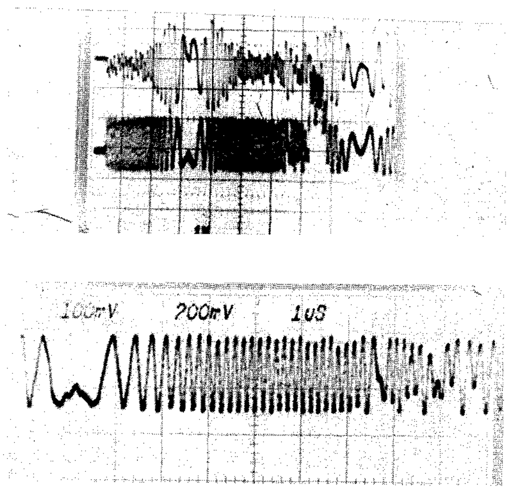

Fig. 2. Photodiode signals (2 μs/div) of the two polarization components of light emerging from an optical fiber looped four times around the current load. The upper trace is from the earliest detector type we fielded, and the lower trace is from a newer EG&G detector with a faster response time and less noise. The current was a damped sine wave typical of an RLC circuit. It started rising 1 μs after the start of trace (a), peaked at 7 μs, decayed until 19 μs, and began to increase again. Modulation of the top trace is from detector noise greatly reduced in the new detector design. In part (b), the center portion of the EG&G detector signal is shown on a 1 μs/div oscilloscope sweep.

Since the sensor measures the magnitude of dI/dt but not its sign, we determined that the places where dI/dt = 0 (7 μs and 19 μs on the traces in Fig. 2a) were actually reversals of the current by measuring the same current with a Rogowski loop. An alternative method would involve splitting the output light from the fiber into two beams; one would be analyzed as shown in Figs. 1 and 2, while the other would be delayed with a quarter wave plate before its polarization analyzer and detectors. With such an arrangement a reversing current would give different signals from a current that rises, levels off (dI/dt = 0), and then rises some more.

Figure 3 shows the oscillograms of signals from the high-speed detector measuring one of the polarization components for a single turn load on a high-explosive-driven flux compression generator seeded by a capacitor bank. The light was from an 830 nm diode laser. Each on-off cycle of the detector represents a 180° polarization rotation, or 1.2 MA of current. Figure 4 shows the current measurement results from these traces. The current peaks at 8.8 MA (6.5 μs after the start of the fast sweep, Fig. 3b) and then begins to decay. We have measured similar currents up to 12 MA.

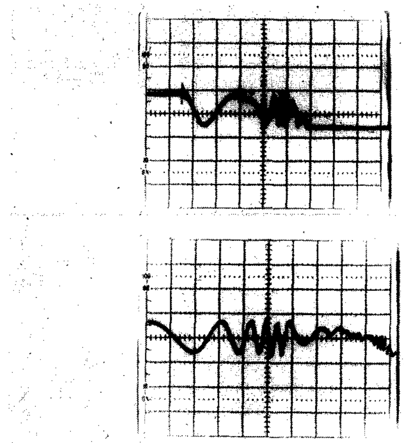

Fig. 3. Oscillograms of the detector output for a high-explosive-driven flux compression generator. The upper trace is at 10 μs/div., and the lower trace shows a portion of the same signal at 1 μs/div. As the increasing load current rotates the polarization plane of the light, the light transmission alternately decreases and increases. Each off-on cycle represents 180° of rotation, or about 1.2 MA of load current. After the load current peak (6.5 μs after the start of the lower trace) the current began to decrease and the polarization rotated back, but shortly thereafter the shock wave hit the fiber and the laser light extinguished.

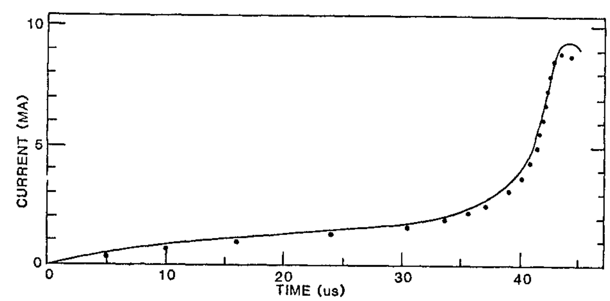

Fig. 4. The compression generator current from the traces of Fig. 2. Zero time is 15 μs after the start of the upper trace of Fig. 2. The curve is from a Rogowski belt, and the points are from the Faraday rotation sensor. The difference in peak magnitudes is within the 5% calibration uncertainties of the sensors.

Future Improvements

We have ordered a piece of polarizing fiber from York V.S.O.P.; it is advertised that this fiber transmits one polarization mode while guiding the other mode into the cladding and out of the fiber, so that in 1 or 2 m of fiber unpolarized light becomes polarized. It offers the possibility of fabricating an all fiber sensor consisting of a laser diode, the low-birefringence fiber in the magnetic field, a short piece of polarizing fiber to analyze the polarization, and a

detector. If necessary, a long piece of fiber could be spliced to the polarization analyzer to carry the modulated light to a distant detector, and polarizing fiber just past the source would permit use of a light-emitting diode or an unpolarized laser diode for more flexibility.

To eliminate fiber stress as a factor in the measurements, we would like to build a fiber optic Sagnac interferometer, such as has been used in rate-of-rotation sensing[5] and is shown schematically in its simplest form in Fig. 5. The laser input light enters a coupler which sends half of the light in each direction around the closed fiber path. Were there no polarization rotation in the fiber, the light having traversed the closed loop and returning to the coupler would interfere constructively with the light that went the opposite direction, giving a signal in the detector (and feedback to the laser). Stress-induced birefringence has identical effects on the light in both paths, and therefore its effects cancel except for possible time-dependent stresses which could affect the different paths at different times, but magnetic field-induced birefringence changes the index of refraction in opposite directions depending on which direction the light passes through the field. Consequently, the detector will see a field-dependent intensity which, for large fields, becomes a series of interference fringes similar to those shown in Figs. 2 and 3.

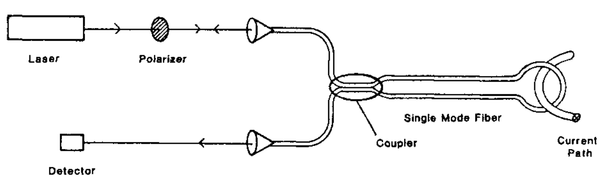

Fig. 5. Schematic diagram of a simple Sagnac fiber interferometer proposed for measuring large currents or magnetic fields with less noise than the sensor we have been using.

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